RESISTIVE WALL HEATING OF THE UNDULATOR IN HIGH REPETITION RATE FELS*

J. Qiang#, J. Corlett, P. Emma, LBNL, Berkeley, CA 94720, U.S.A.
J. Wu, SLAC, Menlo Park, CA, U.S.A.

Abstract

In next generation high repetition rate FELs, beam energy loss due to resistive wall wakefields will produce significant amount of heat. The heat load for a superconducting undulator (operating at low temperature), must be removed and will be expensive to remove. In this paper, we study this effect in an undulator proposed for a Next Generation Light Source (NGLS) at LBNL. We benchmark our calculations with measurements at the LCLS and carry out detailed parameter studies using beam from a start-to-end simulation. Our preliminary results suggest that the heat load in the undulator is about 2 W/m or lower with an aperture size of 6 mm for nominal NGLS preliminary design parameters.

ENERGY LOSSES FORM RESISTIVE WALL WAKEFIELDS

Resistive wall wakefields due to finite conductance of the vacuum pipe can cause significant loss of electron beam energy. Such an energy loss inside an undulator can heat up the vacuum pipe and also induce energy chirp along the beam that will limit the performance of the undulator and the final FEL radiation. In reference [1], the relative energy change due to the resistive wall wakefields was studied at LCLS for a room-temperature normal conducting undulator using a double-horn beam distribution from the LCLS linac. The heating effect to the undulator wall is small at LCLS due to the maximum 120 Hz low repetition rate. For a high repetition rate FEL light source (1 MHz or higher), this effect could be significant. In this paper, we will study both the energy loss to the wall and the induced energy spread inside the electron beam using a beam distribution from the proposed high repetition NGLS at LBNL [2].

Given a wake function $w(z)$ across the electron beam, the total energy loss per meter from a single bunch of electron beam is given by

$$\frac{dE_{beam}}{dL} = \int_{-\infty}^{\infty} \frac{dE(z)}{dL}\rho(z)dz \qquad (1)$$

where

$$\frac{dE(z)}{dL} = \int_{-\infty}^{z} w(z-z')\rho(z')dz' \qquad (2)$$

where z is the electron longitudinal coordinate with the head of beam on the left, ρ is the electron longitudinal line charge density, dE(z)/dL is the energy loss per meter per Coulomb along the beam, and dE_{beam}/dL is the total energy loss of single bunch electron beam. The power loss to the vacuum pipe per meter for a high repetition light source is given by product of the repetition rate and the single bunch total energy loss dE_{beam}/dL. The rms energy spread of the beam induced by such energy loss is given by

$$\frac{dE_{rms}}{dL} = \sqrt{\int_{-\infty}^{\infty}\left(\frac{dE(z)}{dL} - \frac{dE_{beam}}{dL}\right)^2 \rho(z)dz} \qquad (3)$$

The wake function in above equations can be calculated from the impedance by

$$w(z) = \frac{2c}{\pi}\int \mathrm{Re}(Z(k))\cos(kz)dk \qquad (4)$$

where $Z(k)$ is the resistive wall impedance inside the undulator, *Re* denotes the real part of the complex variable impedance function. For a short electron beam inside the undulator, the AC conductivity becomes important. The conductivity of the pipe material is no longer a constant but responses to applied field oscillation. The impedance of the AC resistive wall impedance is given in reference [1] as:

$$Z(k) = \frac{Z_0}{2\pi a^2}\left[\frac{1}{s_0^2}\sqrt{\frac{t_\lambda}{\Gamma k^2}}(i\sqrt{1+t_\lambda} + \mathrm{sgn}(k)\sqrt{1-t_\lambda}) - \frac{ik}{2}\right]^{-1} \qquad (5)$$

where

$t_\lambda = \dfrac{|ks_0|\Gamma}{\sqrt{1+(ks_0\Gamma)^2}}$, $\Gamma = \dfrac{\tau c}{s_0}$, $s_0 = \left(\dfrac{2a^2}{Z_0\sigma}\right)^{1/3}$ is the characteristic length inside the pipe, τ is the relaxation time, σ is the pipe material DC conductance, a is the pipe radius, Z_0 is the vacuum impedance, and c is the speed of light in vacuum.

The above AC resistive wall impedance works well when the mean free path length ($v_f\tau$) is smaller than the classical skin depth δ given by

$$\delta = \sqrt{\frac{c}{2\pi\sigma k}} \qquad (6)$$

where v_f is the Fermi velocity. In the situation of low temperature superconducting undulator, the above condition might not be valid. This is also called anomalous skin effect (ASE). The resistive wall impedance under ASE is given by [3]

$$Z(k) = \frac{2Z_0(Ba)^{3/5}}{\pi a^2}\frac{\bar{k}^{2/3}}{1+i(\sqrt{3}-2\bar{k}^{5/3})} \qquad (7)$$

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#jqiang@lbl.gov

where $B = \left(\frac{\sqrt{3}}{16\pi Z_0} l / \sigma_c \right)^{1/3}$, $\bar{k} = k(Ba)^{3/5}$, and l is the mean free path of the conducting electrons.

BENCHMARK WITH LCLS MEASUREMENTS

At LCLS, energy loss of 250 pC electron beam inside an undulator with 5 mm aperture size and 132 meter length Al rectangular pipe was measured at 13.64 GeV energy with a peak current of 3 kA. The energy loss inside the FEL undulator including both the spontaneous radiation loss and the wakefields induced energy loss was measured by kicking the electron bunch to turn the FEL process off. The spontaneous radiation induced the energy loss was obtained by setting each undulator section as "out" status and measuring the energy loss as a function of the number of undulator segments. The difference between those two measurements gives the energy loss from the wakefields inside the undulator, which is about 40 MeV. Following above theoretical models, we also calculated the energy loss from the resistive wall impedance model at room temperature using a double-horn current distribution given in Figure 1.

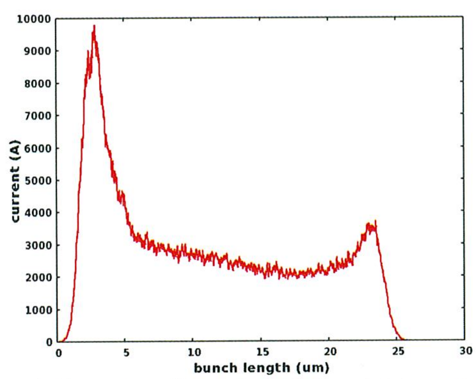

Figure 1: Current profile at the LCLS undulator entrance.

The energy loss across the electron beam is obtained and given in Figure 2.

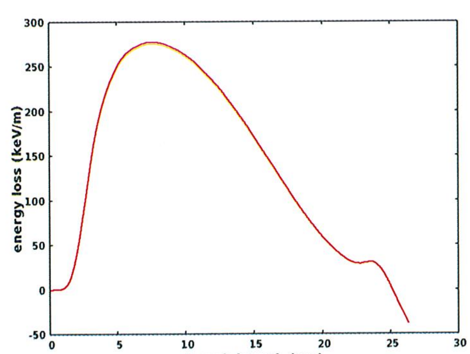

Figure 2: energy loss along the beam for an LCLS current profile at 13.64 GeV.

The total energy loss per bunch is 3.76e-5 J/m. Taking into account the undulator length of 4x33 meters, this results in an energy loss per electron of about 20 MeV, which is within a factor of 2 in agreement with the experimental measurement (40 MeV).

RESISTIVE WALL HEATING IN NGLS UNDULATORS

The NGLS is a next generation high repetition soft X-ray FEL light source that will have an averaged beam power of 720 kW with a nominal 300 pC electron charge and 1 MHz repetition rate [2]. Such a high average beam power can lead to significant beam pipe heating and beam energy spread growth. Using a beam current distribution from the NGLS linac output as shown in Figure 3 [4] , we calculated the power loss to the vacuum pipe wall and the energy loss across the beam.

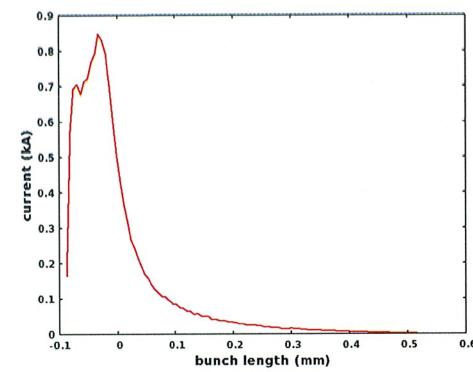

Figure 3: Current profile at the exit of the NGLS beam delivery system at 2.4 GeV.

Figure 4 shows the power loss per meter inside the undulator as a function of pipe aperture size with two types of conducting materials, Al and Cu. It is seen that the Cu pipe gives somewhat smaller heat load to the conducting wall than the Al pipe does. For an aperture size beyond 6 mm, the power loss is about 2 W/m. Besides heating the vacuum pipe, the resistive wall wake field also causes the correlated energy spread along the beam.

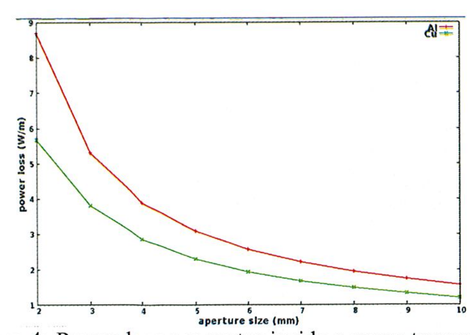

Figure 4: Power loss per meter inside a room temperature normal conducting NGLS undulator as a function of aperture size. The red line is from the Al pipe, the green one is from the Cu pipe.

Figure 5 shows the energy loss across the electron beam inside an undulator with an aperture size of 6 mm. The energy loss variation inside the Al pipe shows less variation than that inside the Cu pipe.

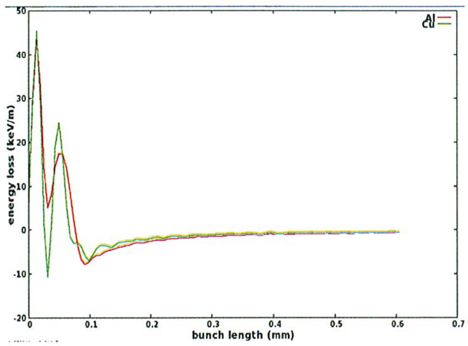

Figure 5: Energy loss through the beam inside the normal conducting undulator pipe with an aperture size of 6 mm. The red line is from the Al pipe, the green one is from the Cu pipe.

The low temperature superconducting undulator is also being proposed for the NGLS. It has the advantages of high field strength and allowing for shorter undulator period. A high deposition of heat load from the resistive wall wakefields could quench the superconducting undulator and requires significant amount of cooling power to remove these heat. Figure 6 shows power loss per meter inside a low temperature superconducting NGLS undulator as a function of aperture size with an Al pipe and a Cu pipe. It is seen that both materials produce very similar power loss. For an aperture size of 6 mm, the power loss is even below the 2 W/m.

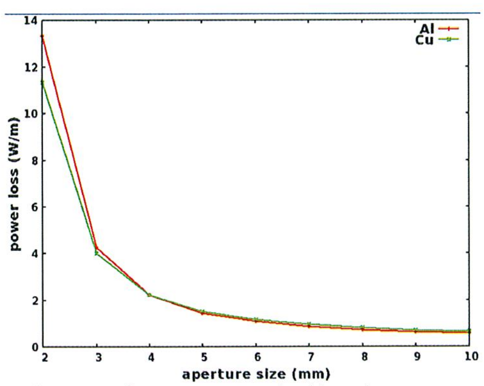

Figure 6: Power loss per meter inside a low temperature superconducting NGLS undulator as a function of aperture size. The red line is from the Al pipe, the green one is from the Cu pipe.

The energy loss along the beam is also calculated with 6 mm aperture inside an Al and a Cu undulator. Both materials show similar energy loss distribution along the beam. The rms energy spread induced by such energy loss is about 8.4 keV/m for the Al material and 7.2 keV/m for the Cu material.

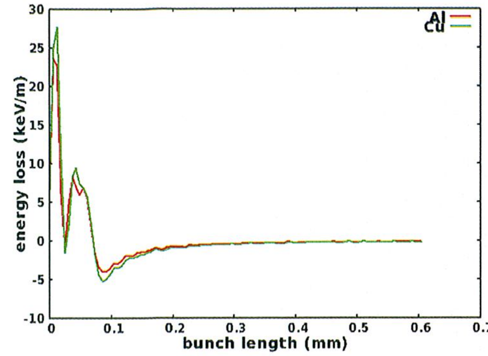

Figure 7: Energy loss along the NGLS beam inside the superconducting undulator pipe with an aperture size of 6 mm. The red line is from the Al pipe, the green one is from the Cu pipe.

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